DARPA Grand Challenge 2005

Technical Paper

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Abstract

Novel approaches that distinguish Red Team's desert racing include multifusion, which combines on-board sensing with preplanning information, drive-by topography for pre-mapping terrain, stabilized sensor pointing which facilitates superior world modeling, and swerving to achieve high-speed avoidance maneuvers. These distinctive technologies, combined with solid implementation of well-known basics like pose estimation, waypoint following and path tracking drive Red Team's "Sandstorm" robot. Sandstorm is an automated Humvee that has logged 3,200 miles of autonomous driving including demonstrations of Grand Challenge-like distance and qualifier and speed scenarios. This paper profiles the configuration, operation and testing of Sandstorm.

Introduction

The Red Team is a collaborative enterprise of students, volunteers, professionals and corporations led by Carnegie Mellon. Sandstorm is the Red Team's autonomous ground vehicle.

A vigorous testing program has demonstrated reliable, high-speed navigation including a 7-hour 200-mile endurance run, reliable obstacle avoidance at 35 mph and peak speed of 54 mph.

1   Vehicle Description

1.1   Sandstorm – 1986 M998 High Mobility Multi-Wheeled Vehicle

Sandstorm is a modified 1986 AM General M998 HMMWV (Figure 1). The HMMWV is selected for its ground clearance, dynamic stability, large payload capacity and ruggedness. A custom aluminum body and a cooled, shock-isolated electronics bay replaced the crew compartment body panels, doors, seats and windshield. A 5 kW auxiliary generator provides power to the electronics payload. The vehicle is 84 inches (2.13 m) wide, 214 inches (5.43 m) long, and 107 inches (2.72 m) tall. Fueled race weight is 7,800 lbs.

1.2   Drive Train and Suspension Modifications

Sandstorm's drive train features a 6.5 liter turbo diesel, automatic transmission, four-wheel drive transfer case, half-shaft axles and in-hub final gear reduction. The chassis suspension utilizes custom coil-over struts with nitrogen reservoirs (Figure 2). Sandstorm's electronics enclosure is

suspended with 12 shock isolators, each of which is a coil over strut shock absorber (Figure 3). These two levels of suspension serve (1) to protect Sandstorm's sensitive electronics and computing hardware and (2) to smooth sensor trajectories.

Figure 1 – Sandstorm shown operating during a 20 mile run on steep, winding grades on 31 July 2005 at a strip mine in Berlin, PA.

Figure 2 CustomCoil Over Strut Suspension
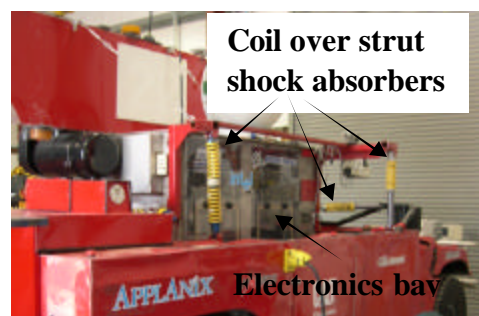
Figure 3 Electronics Bay with Shock Isolation

2 Autonomous Operations

2.1 *Processing*

Sandstorm processes sensing, planning, and driving in a repetitive, end-to-end navigation loop that typically cycles in a fifth of a second. Nested loops within this processing cycle are typically 100 Hz. Processes are distributed over eleven (11) general purpose computers more fully described below.

2.1.1 Computing Systems

Sandstorm's sensors, controllers, and devices embed DSPs, FPGAs, and ASICS, but general purpose computers provide the main processing power.

2.1.1.1 Hardware

Sandstorm has eleven (11) general purpose computers. There are four (4) Pentium III PC 104 stacks and seven (7) Pentium M Compact PCI computers. Table 1 indicates the function of each. The selection of the computing hardware was based on processing capacity, form factor, interface extensibility and power consumption. Sandstorm is equipped with a 1 Gbit/s Ethernet network. Interface to Sandstorm's drive by wire system is via Controller Area Network (CAN) bus. The interfaces for Sandstorm's sensors are listed in Table 2 in the Environment Sensing subsection.

Type	Quantity	Function
Pentium III PC104 stacks.	4	1. 360° RADAR interface 2. Long range LIDAR interface 3. Power switching control 4. Gimbal control
Pentium M Compact PCI computers.	7	1. Short range LIDAR interface 2. POSE data acquisition 3. Terrain analyses 4. Map data management 5. Data transfer to path planner 6. Path planning & tracking 7. Drive-by-wire interface

Table 1 - Sandstorm's Computing Hardware

2.1.1.2 Software

A million lines of code compute models from sensor data, plan paths and speeds, command devices, and navigate Sandstorm. The software, written in C++, runs under a Fedora Core kernel running a 100 Hz clock.

2.1.1.3 Reliability

Mean Time Between Failure (MTBF) for computing and network hardware is 20 hours and MTBF for utility software is 200 hours. Navigation MTBF (for incidents like clipping a berm or grazing an obstacle) is highly dependent on route difficulty.

Sandstorm control system is single string with a few instances of redundant sensors but has no command redundancy. A Vehicle Health Management system monitors the run status of processes via a UDP based shared memory status message. The status message includes start time, last run time, cycle time, initialization time and heart beat counter. From these status messages the health manager can determine the following:

- Initialization Successful if ((Current Time – Start Time) < Initialization Time) and (Heart Beat Counting)
- Process Blocked if (Last Run Time > Cycle Time) and (Heart Beat Counting)
- Process Health Good if (Last Run Time < Cycle Time) and (Heart Beat Counting)
- Process Dead if Heart Beat Not Counting

In the event a process is determined to have failed initialization, is blocked or is dead, the health manager restarts the process. The health of Sandstorm's 11 computers is determined by a periodic TCP/IP Ping from the health manager to each computer. In the event that any of the computers fails to respond, the health manager pauses the vehicle (Remove throttle and apply full brake) power cycle the machine and waits for it to reinitialize and activate its processes. Machine and process restart is managed by the health manager.

Sandstorm's electromechanical configuration has been frozen since June 1, 2005. The Red Team sustains a rigorous reliability program that identifies incidents, fixes faults, tests results and tracks recurrence. Mean-time-to-repair a fault is 18 days.
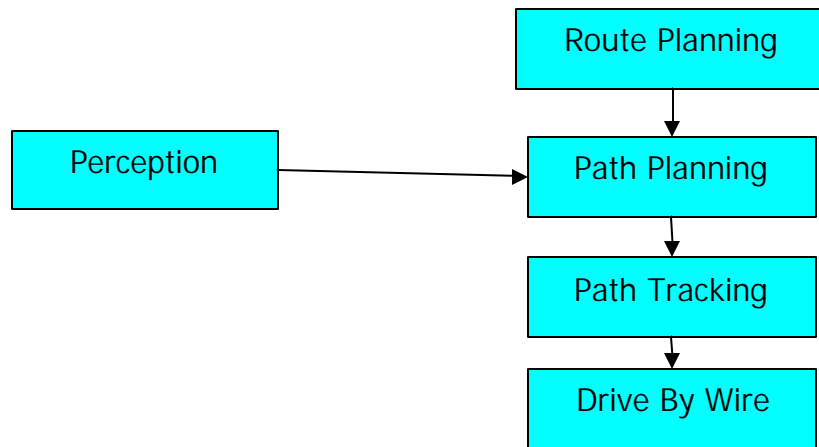
2.1.2   System Architecture

Figure 4 Sandstorm's System Architecture

2.1.3   Development Process

The Red Team set goals and established evaluation criteria at the beginning of each 100-day development phase, then produced, tested and evaluated capabilities to meet the 100-day goals.
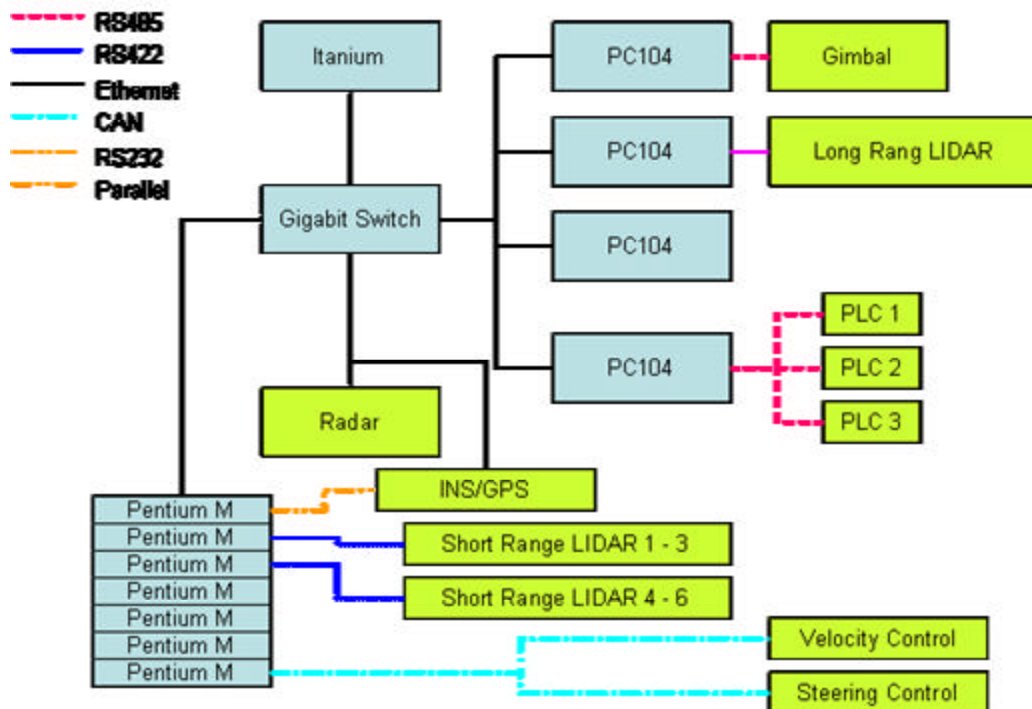

Figure 5 Sandstorm's Network Topology

2.2 Localization

2.2.1 GPS/INS

Sandstorm estimates 6-axis pose, velocity and acceleration (latitude, longitude, altitude, roll, pitch, yaw) by combining inertial sensing, GPS data and odometry using a Kalman filter. The INS/GPS (Applanix POS LV) is a strapdown inertial navigation platform, featuring high-bandwidth, low-latency, GPS with azimuth measurement and distance measurement indicator. A differential GPS receiver (Trimble AG132 with Omnistar VBS corrections) augments the INS/GPS's two antennas to enhance position estimation. The INS/GPS platform typically calculates vehicle position and orientation data with ½ meter accuracy. It sustains usable pose estimation despite GPS dropouts lasting over several minutes.

2.2.2 Map Data

An off-board route planning system incorporates elevation topology, satellite imagery and drive-by topography data. The map data is sparse relative to the possible GC routes. The planning process designates contexts like paved road, dirt trail or underpass. The race planners refine a preplanned route and set intended speeds compliant to the race data definition file. Just prior to race start Sandstorm receives a path definition file (PDF) consisting of waypoints, coordinates, speeds and contexts defined for every meter along the race route.

2.3 Sensing

Sandstorm employs long range LIDAR, short range LIDAR and RADAR sensors for mapping terrain and detecting obstacles, roads, and other vehicles. Table 2 lists Sandstorm's perception sensors with their primary functions, sensing horizon, and mode of operations.

2.3.1 Sensor Mounting Locations

An actuated three-axis gimbal points and stabilizes the long range single line LIDAR used for mapping terrain topology and detecting obstacles (Figure 6). Stabilization of the LIDAR increases the fidelity of the terrain map and the accuracy of the obstacle localization. Pointing enables Sandstorm to look aside before turning and to rescan missed or questionable portions of the terrain map. The effective field of view with pointing is 240 degrees (180 degree gimbal yaw plus 60 degree laser scanner field-of-view) with sensor coverage of 5-150 meters. The gimbal

resides in a protective carbon fiber dome on top of the shock isolated electronics bay, to reduce bandwidth requirements of the actuators.
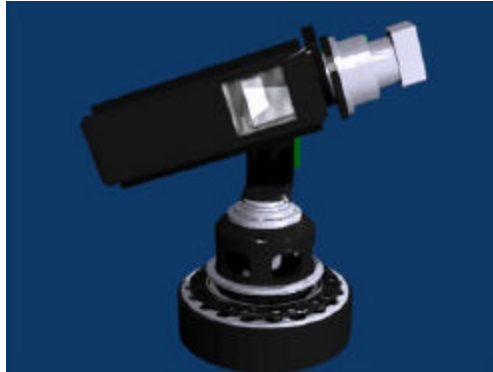
Figure 6 Three Axis Gimbal with Long Range LIDAR Payload.

Four (4) short range LIDAR line scanners (+/- 90 degrees 50 m) are mounted on the brush guard on the front of the vehicle. These LIDARs detect obstacles and characterize the terrain. Two (2) short range LIDARs are mounted on the shock isolated electronics bay. These sensors are used for terrain topology mapping and for obstacle detection. Fusion of these sensors generates a range model that spans 200 degrees. The 360 degree RADAR used for obstacle detection is mounted on the brush guard. Most of the RADAR's scan is obscured by the vehicle or brush guard. Its effective field of view is 70 degrees 40-70 meters in front of the vehicle. One color camera is mounted on the starboard shoulder of the electronics bay to record visual documentation and is not part of the navigation sensor suite. Figure 7 shows the mounting configuration of the sensors.
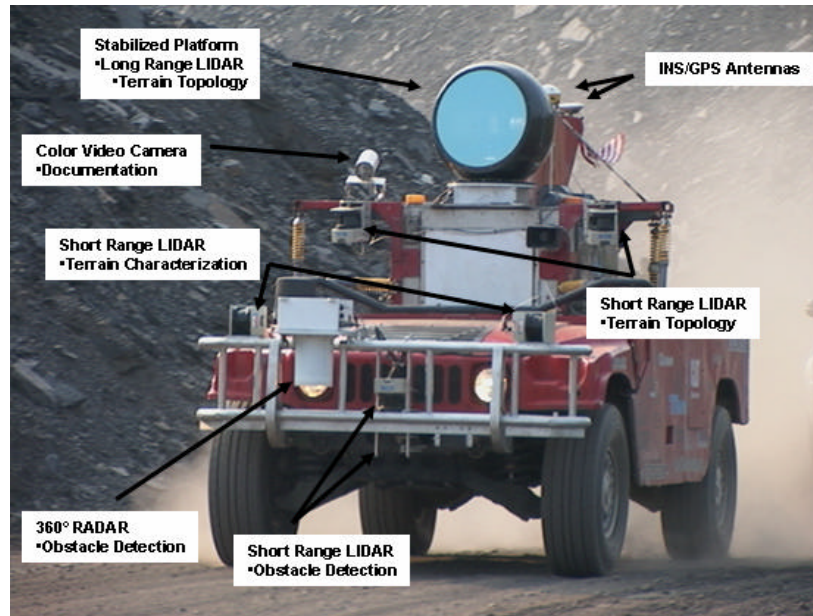
Figure 7 Sensor Mounting Locations

Sensor	Quantity	Interface	Range/Field of View	Primary Function
Long Range LIDAR line scanner	1	ECP compatible Parallel Port	150m (varies with gimbal pitch) with 60 degree field of view	Terrain topology mapping, obstacle detection and characterization
LIDAR line scanner	6	RS422	50m (Shoulder mounted pointed with 15m look ahead) with 180 degree field of view	Terrain topology mapping, obstacle detection and characterization
360° RADAR	1	Ethernet	200 meters (Effective range is 40 to 70 meters) Using ~70 degree field of view	Obstacle detection
Video Camera	1	IEEE 1394	N/A	Visual documentation
GPS/INS	1	Ethernet/RS 232	Position, velocity and acceleration for all axis. Antennas mounted along the top of the fin.	Position sensing and pose estimation.

Table 2 - Sandstorm's Sensors

2.3.2 Sensing Architecture

Sandstorm's perception system field of view is shown in Figure 8 (The 60 degree wedge of long range LIDAR can be swept 180 degrees by the gimbal for a total field of view of 240 degrees). Fusion of perception data is via a terrain cost map and binary obstacle map. Terrain cost maps are generated by evaluating the relative height of a sensed area to its neighbors and assigning a cost of 0 to 255 to that area. Binary obstacle maps are created in a two step process. First, an object detection algorithm, customized for each sensor group, detects and localizes obstacles. Second, detected obstacles are written into a map at the detected location.

2.3.3 Vehicle State Sensing

Sandstorm's state sensing monitors and measures equipment temperature, actuator position, velocity and acceleration. State is sensed via optical encoders, potentiometers, rotational variable differential transformers (RVDT), thermocouples, current and voltage sensors. Vehicle state sensors feed Vehicle Health Management which monitors state and restarts some resources via power cycling in the event of a sensed failure.
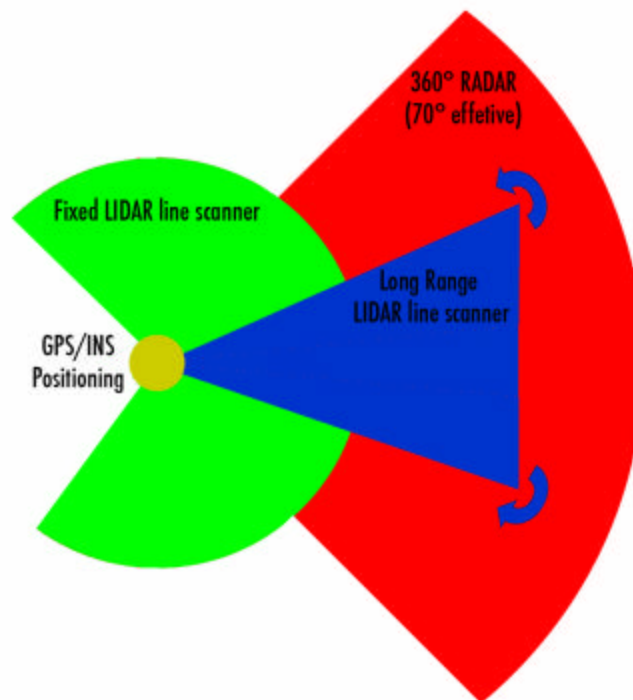

Figure 8 Sandstorm's Perception Field of View

2.3.4 Sensing to Actuation System

2.3.4.1 Waypoint Following

Path tracking evaluates a best path relative to current vehicle position and pose. The algorithm sets maximum speed and curvature and constrains the trajectory to ensure against skidding and tipover. Path tracking passes calculated commands of desired curvature and speed to the vehicle's drive-by-wire system.

2.3.4.2 Path Finding

The path definition file generated from the RDDF during pre-race planning is fused along with LIDAR and RADAR data into a composite model. The world model consists of the terrain cost map and binary obstacle map discussed in section 2.3.2. Items in the binary obstacle map are fused to the terrain cost map by adding them as high or infinite cost, while clear traverses are added as low or no cost.

Path planning uses an A-star algorithm which considers multiple possible traversable arcs forward of vehicle position within the RDDF defined route corridor. Each possible arc is evaluated in terms of least cost to goal. The "best" path at any given interval is then communicated to a path tracking algorithm. Areas outside of the path definition file's route corridor are not considered in path planning.

2.3.4.3 Obstacle Detection

Sandstorm detects obstacles with its RADAR and two short range LIDARs mounted in the center of the brush guard.

Radar data is filtered to recognize returns on order of meter-scale (like people, poles and garbage cans) that are isolated from surrounding clutter like dense vegetation. Objects detected by radar are tracked and shrunk in the binary obstacle map as they are approached by Sandstorm. This

shrinking accounts for wedge shaped range bins and multiple obstacles detected at long range in a single bin.

The short range LIDARs are mounted in a stacked manner such that their line scans are parallel. This arrangement allows Sandstorm to differentiate between obstacles and hills.

The long and short range LIDARs mounted on the electronics bay are primarily for terrain topography. However, these sensors will sense obstacles and mark them as high cost in the terrain cost map. Sandstorm will avoid these high cost areas.

2.3.4.4 Collision Avoidance

Collision avoidance modifies the preplanned route to swerve around a sensed obstacle represented as terrain with very high cost. The path planner generates the swerve maneuver by modifying the location of 1 meter spaced waypoints. The path tracker limits the swerve maneuver by enforcing preset maximum speeds for vehicle dynamic performance accounting for terrain, curvature and slope.

2.3.4.5 Vehicle Control Models

Sandstorm's braking, steering and propulsion are specialized from PID fundamentals. Sandstorm's mechanical, electromechanical, and electrohydraulic system dynamics and controllers are modeled using Simulink™. The Simulink models are compiled into C code and downloaded to Sandstorm's drive-by-wire controllers. Control parameters are tuned and tested in field conditions.

2.3.4.5.1 Velocity

Velocity is regulated by a proportional-integral (PI) controller that commands either a throttle actuator position or a brake actuator position. The inner loop brake actuator position controller is a PI controller and the throttle actuator position controller is a proportional controller with different gains to account for the significant differences between the throttle dynamics and the brake dynamics. The velocity controller receives a velocity command from the path tracker. The controller senses velocity by reading odometry.

2.3.4.5.2 Steering

The steering controller uses a proportional-integral-derivative (PID) controller. The controller receives a curvature command from the path tracker. The controller senses steering position through a RVDT and actuator position feedback. The RVDT is the primary sensor for the steer by wire system. In the event of loss of data from the RVDT the control algorithm will operate based on the actuator position feed back and a lookup table of relative steering curvature.

2.3.4.5.3 Transmission

Sandstorm's transmission is an automatic three-speed. The drive by wire shifter only designates forward (drive), reverse and neutral on the transmission. The transmission automatically shifts itself among first, second and third gears within the selected range. Sandstorm shifts to forward, reverse or neutral by commanding an actuator which moves the transmission shift. The closed loop control of the linear actuator uses a proportional controller once "forward" is selected.

2.4 Vehicle Control

2.4.1 Autonomous Operation Contingencies

2.4.1.1 Missed Waypoint

Sandstorm's navigation is robust to missed waypoints. It complies with corridor constraint, but there is no requirement that the vehicle must go through any one waypoint. The vehicle path is continuously updated with respect to the current position and the desired route through the corridor. Sandstorm continuously recomputes its desired path.

2.4.1.2 Vehicle Stuck

Sandstorm detects wheel slip by comparing the speed output from the distance measurement sensor to the speed reported by the pose estimation system. When the velocity controller detects wheel speed over 5m/sec and velocity of 0m/sec, it will back up along the path 10m, clear its current terrain cost map and binary obstacle map, pan and scan with long range LIDAR and RADAR, plan a new path and attempt to drive around any obstacles. In the event, this maneuver does not work, Sandstorm can modulate the throttle or brake in attempt to get un-stuck or actuate the throttle and brake simultaneously to engage the mechanical differential locks.

2.4.1.3 Vehicle outside Lateral Boundary

The vehicle planner operates on a world model represented as a cost map as described in section 2.3.4.2. Regions outside the lateral-boundary-offset are set at infinite cost in the map. In the event that Sandstorm ends up outside the boundary the planner will modify the path in order to get the vehicle back to an area of lower cost, which should be inside the boundary.

2.4.1.4 Obstacle in Path

Obstacles are represented in the cost map with varying costs similar to the lateral-boundary case. The planner reacts to those obstacles by planning through the path of least cost, reference sections 2.3.4.3 and 2.3.4.4.

2.4.2 Special Vehicle Maneuvers

Sandstorm has the robustness to accommodate the irregular terrain that it encounters. The control system that manages the vehicle speed has the ability to ramp the throttle and or brake to ensure that speed is maintained when traversing up or down hills. Tight and off camber turns are predicted using the pre-planned path, and vehicle speed is lowered accordingly using vehicle dynamics to ensure traction and stability.

When Sandstorm detects that its current heading is more than 30 degrees off its desired heading, it will stop and backup along a preplanned arc until an acceptable heading is achieved. This situation occurs if the vehicle has experienced a spinning slide or attempts to turn an extremely sharp curve. Sandstorm used this maneuver during the 2004 DARPA Grand Challenge after hitting a large rock.

2.4.3 Integration of Navigation and Sensing

Sandstorm drives based on a preplanned path definition file (PDF) derived from the RDDF during preplanning, reference section 2.2.2. The PDF's waypoints are defined as Universal

Transverse Mercatur (UTM) coordinates. Sandstorm's integrated worldview (PDF, terrain cost map and binary obstacle map) is localized in UTM coordinates. Integration of PDF and cost map occurs during path planning, reference section 2.3.4.2.

2.4.4 Vehicle Control when not in Autonomous Mode

Sandstorm can be switched out of autonomous mode for manual operation. To do this a main switch disables the drive-by-wire controllers, and a secondary switch cuts the connection to the steering motor to prevent back-driving. A removable steering wheel must be attached for steering, and brake and throttle actuation occur as in a normal vehicle. In manual mode, the navigation computing may still run, but the vehicle control system will ignore automatic commands.

2.5 System Tests

Red Team has been testing Sandstorm's systems and subsystems since it became operational in December of 2003. Sandstorm has accumulated over 3000 autonomous test miles. Notable tests include:

1. 200 miles on the Beaver Run Raceway averaging 26.4 MPH with a peak speed of 38.2 MPH.
2. More than 100 miles of testing on soft, winding road on the Nevada Automotive Test Center's Sand Serpentine.
3. Extensive Perception Planning, Perception Tracking and Blind Tracking tests on a modified ISO 3888-1 Severe Lane Change Maneuver course.
4. Repeated traverse of a 28-mile section of the Pony Express Trail at race pace.

In addition to these system tests, Sandstorm has tested for software endurance via simulation, dust detection, pointing, shock and vibration.

With thirty-five days remaining to the Grand Challenge qualifier, the Red Team exhibits race-worthy performance and viable reliability. Planned tests include end-to-end race day simulations, 100 mile traverses of trails and hills with challenges like gates, high-speed, underpasses and difficult terrain.